Conclusions and Recommendations from the IMPACT Project WP2: Breach Formation

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SUMMARY
This paper presents an overview of work undertaken within the IMPACT Project WP2: Breach Formation.

1 INTRODUCTION
Research under work package 2 (WP2) of the IMPACT project focuses on our ability to predict breach formation through a dam or flood defence embankment. The core work links field and laboratory testing (to collate reliable data sets and understand basic breach formation processes) with numerical model testing, comparison and development. In addition, consideration is given to factors affecting breach location (links via WP6) and also the uncertainty associated with breach modelling is also investigated (WP5). A more detailed description of the work plan can be found in the Description of Work (DoW), sections WP2.1-2.4, WP5 and WP6.

The core research work entailed a considerable number of field and laboratory tests and the collation of large data sets. This paper provides a brief overview of the work and key issues. More detailed information can be found via the WP2 technical report.

2 FIELD AND LABORATORY DATA
2.1 Objective and approach
Objectives of the modelling work undertaken through WP2 of the IMPACT project are to:
• Establish a better understanding of the embankment breaching process
• Provide data for numerical model validation, calibration and testing, and hence improve modelling tools performance
• Provide information / data to assess the scaling effect between field and laboratory experiments
• Identify best approach /approaches to simulate breach formation through embankments
• Assess and quantify the level of uncertainty of the current breach modelling techniques

The work divided into 3 clear packages, namely field modelling, laboratory modelling and numerical modelling / analysis (see Figure 1).
2.2 Data collected
Extensive sets of field and laboratory data were collected. A range of data was recorded for each test, including water levels, flow and extensive photo and video footage. This data relates to the following DoW deliverables:

- D2.1.3 First field test failure programme
- D2.1.5 Second field test failure programme
- D2.2.1 Physical modelling test series#1
- D2.2.2 Physical modelling test series#2
- D2.2.3 Physical modelling test series#3

2.2.1 Field Data
In Years 1 and 2, five field tests were undertaken in Norway. The five tests were designed to provide large scale data on breach formation processes in homogeneous and composite embankments, failing by overtopping and piping. The location of the test site is shown in Figure 2 below.
The five tests comprised:
1. 6 m high cohesive embankment / overtopping (25 % clay and less than 15% sand)
2. 5 m high non-cohesive embankment / overtopping (less than 5 % fines)
3. 6 m Composite embankment / overtopping (Rock fill & Moraine)
4. 6 m Composite embankment / piping (Rock fill & Moraine)
5. 4.5m Homogeneous embankment / piping (Moraine)

In general, the following data was collected from each field test:
1. Water level at locations up and downstream of the embankment
2. Flow released from the upper reservoir into the ‘test reservoir’
3. Pore water pressures in the embankment
4. Breach development (time development of breach based upon movement sensors)
5. Digital cameras and videos up and downstream monitoring breach development

A detailed description of the various tests is given in the WP2 technical report. Figures 3-7 below show each of the five tests at various stages of failure.

Figure 3: Breach development stages (Field Test #1: Cohesive, homogenous)
Figure 4: Breach development stages (Field Test #2: Non-cohesive, homogenous)

Figure 5: Breach development stages (Field Test #3: Composite, moraine core)
Figure 6: Breach development stages (Field Test #4: Composite, moraine core, piping)

Figure 7: Breach development stages (Field Test #5: Homogeneous, moraine, piping)
2.2.2 Laboratory Data
A total of 22 laboratory experiments have been undertaken at HR Wallingford in the UK. The overall objective of these tests was to better understand the breach processes in embankments failed by overtopping or piping and identify the important parameters that influence these processes. These tests were divided into 3 series. Table 1 shows the details of each series of tests. The focus, in this paper, is on the analysis of series #1 and #2.

<table>
<thead>
<tr>
<th>Series #1 (9 tests) [Fig 8]</th>
<th>Laboratory Test Description</th>
<th>Laboratory Test Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This series of tests was based around the homogeneous non-cohesive field test at scale of 1:10. Each embankment was built from non-cohesive material, however, more than one grading of sediment were used along with different embankment geometry, breach location and time before failure (seepage effect).</td>
<td>To better understand breach formation processes and to identify the effect of a variety of parameters on these processes in homogeneous non-cohesive embankments failed by overtopping</td>
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<table>
<thead>
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<th>Series #2 (8 tests) [Fig 13]</th>
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<td></td>
<td>This series of tests was based around the homogeneous cohesive field test at scale of 1:10. Each embankment was built from cohesive material, however, two different grading of sediment were used along with different embankment geometry, compaction effort and moisture content.</td>
<td>To better understand breach formation processes and to identify the effect of a variety of parameters on these processes in homogeneous cohesive embankments failed by overtopping. Assess initiation of the piping mechanism and dimensions for the homogeneous field test. Provide information about the pipe formation to assist in development of the field test failure mechanism.</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Series #3 (5 tests)</th>
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<td></td>
<td>Material brought from a UK flood embankment. Samples were 1m (W) x 1m (L) x 0.8m (D)</td>
<td>Monitor piping initiation and development</td>
</tr>
</tbody>
</table>

Table 1: Laboratory tests description

Series #1 - breach processes
The following processes were observed during the breach formation for this series of tests:
1. Water erodes the downstream slope and the slope becomes milder. Head cutting was not observed in this series of tests
2. The crest of the embankment retreats and erodes downward
3. Once the breach is fully developed (i.e. material is nearly eroded to the base), the material below the water level is eroded. This undermines the slopes and leads to block failure
4. The above processes continue until there is not enough water to erode more material
5. Upstream slope erosion was also observed leading to a curved ‘bell mouth’ entrance to the breach. This ‘bell mouth’ weir controlled flow through the breach. Slumping was also observed on the upstream face due to this erosion.

Series #1 - effect of various parameters on the breach processes
The effect of various parameters such as grading and geometry was examined in this series of tests. In the following sections, the effect of these parameters is presented.
The following three different gradings have been used to examine the effect of material grading on the breach processes:

1. Uniform coarse grading with $D_{50} = 0.70-0.90$ mm
2. Uniform fine grading with $D_{50} = 0.25$ mm
3. Wide grading (4 types of sand were used) with $D_{50} = 0.25$ mm

Figure 9 shows the outflow and inflow hydrograph and breach top width growth with time for grading 2 and 3. It can be seen that little effect is shown in this figure in terms of peak outflow value, time to peak and breach growth rates and final breach width. These two runs show that the effect of grading is insignificant at this laboratory scale. Note that the issue here is scale effect. It is considered unlikely that material grading will not affect breach growth at prototype scale.
Effect of Breach Location
To examine the effect of the breach location, the initial breach notch was placed once on the centre and once on the side of two different embankments with similar properties and same geometry. Figure 10 shows the outflow and inflow hydrograph and breach top width growth with time for these two tests.

Effect of geometry changes
The following two geometry variations were tested in this series:
1. Upstream and downstream slopes were increased to 1:2 instead of 1:1.7
2. Crest with was increased to 0.3 m instead of 0.20 m

Figure 11 shows the outflow and inflow hydrograph and breach top width growth with time for the slope variation tests. It can be seen that increasing the slope has delayed slightly the
erosion and the time to peak outflow, but, peak outflow value and final breach width were very similar.

![Figure 11: Slope variation results](image1)

Figure 11 shows the outflow and inflow hydrograph and breach top width growth with time for the crest width variation tests.

![Figure 12: Crest width variation results](image2)

Figure 12: Crest width variation results

It can be seen that increasing the crest width had nearly no effect on the peak outflow, time to peak, and erosion rates for these two runs. In general, the effect of geometry changes was insignificant at this laboratory scale for this series of tests.

**Series #2 - breach processes**

The following processes were observed during the breach formation for these tests:
1. Head cutting was observed on the downstream face contrary to the smoothing process observed in series #1. More than one head cut was formed (See Figure 13A)
2. The head cuts combine into one deep head cut and this migrates upstream and then erodes downward
3. Once the breach is fully developed (i.e. material is nearly eroded to the base), the material below the water level is eroded. This undermines the slopes and lead to block failure
4. The above processes continues until there is not enough water to erode more material.
5. Upstream slope erosion was also observed producing a similar bell mouth shape to Series #1. Again, slumping was also observed on the upstream face due to this erosion.

Processes 3, 4, and 5 were very similar to series #1 except that the frequency of material slumping was lower in this series. Breach widening erosion rates and final width were also smaller than those observed in Series #1. Figure 13 shows the above processes.

Figure 13: Series #2 - breach processes

Series #2 - effect of various parameters on the breach processes
The effect of various parameters such as grading, compaction, water content, and geometry was examined in this series of tests. In the following sections, the effect of these parameters is presented.

Effect of material type and grading
The following two material grades were used to examine the effect of material type and grading on the breach processes:
1. Fine-grained clay material with $D_{50} = 0.005$ mm with 24-43% of clay (This was used for all the tests except one where the moraine material was used)
2. Moraine material with $D_{50} = 0.715$ mm with less than 10% fines.

Figure 14 shows the outflow and inflow hydrograph and breach top width growth with time for the material variation tests. It is quite clear that the moraine material was more erodible than the clay material. This has accelerated the erosion process and led to a higher peak outflow and larger final breach width.
Effect of compaction

Two compaction efforts were used, to examine the effect of compaction on the clay material, with one compaction effort half of the other. Figure 15 shows the outflow and inflow hydrograph and breach top width growth with time for the compaction variation tests. Halving the compaction had an impact on the breaching processes for these two test cases but that impact is clouded by the effects of the compaction water content which is discussed in the next section. The decrease in compaction effort has accelerated the erosion process and led to a higher peak outflow and final breach width at this laboratory scale. The compaction water content for the higher compaction effort case was 25% and the half compaction effort case was 22%. This decrease in water content, as discussed in the next section, also accelerates erosion rates.
Effect of water content
To check the effect of the compaction water content, two different values of water content were used. The first was very near to the optimum water content (30 %) for the material used in this series of tests. The other was the natural water content of this material (24 %) which is lower than the optimum water content value.

![Figure 16: Water content variation results](image)

The compaction effort for these two tests was basically the same therefore, the effect on erosion and outflow can be attributed to changes in the compaction water content. Figure 16 shows the outflow and inflow hydrograph and breach top width growth with time for the water content variation tests. Changing the water content to the optimum has significantly change the erosion properties of the material used. The embankment with optimum water content resisted failure and at the end of the test only partially failed with a smaller breach width and a lower peak outflow value compared to the other embankment. Laboratory tests, undertaken using the Jet-Test apparatus (ASTM, 1996), showed a difference in the erodibility of about 93 % between the two embankments.

Effect of geometry changes
The following two geometry variations were tested in this series:
1. Downstream slope was changed to 1V:1H instead of 1V:2H
2. Downstream slope was changed to 1V:3H instead of 1V:2H

Figure 17 shows the outflow and inflow hydrograph and breach top width growth with time for the slope variation No. 1. Both tests, the test with 1V:1H and the test with 1V:3H slopes, sped up failure and led to a higher peak outflow. This was not expected for the 1V:3H slope embankment as it had more material that the other two slopes (i.e. longer failure time). This could be due to the fact that both tests were at a lower bulk density than the 1V:2H slope and also at lower water content. These issues clouded the outcome of both tests and made the results of these two tests inconclusive.
3 BENCHMARK TESTS OF CURRENT MODELS

3.1 Objective and test description (overview)

Extensive numerical modelling has been undertaken by selected members of the IMPACT project team and the value of model comparison was enhanced by additional participation from modellers world-wide (See Table 2 for details). A significant number of numerical model runs has been undertaken as blind tests to ensure complete objectivity. Blind means that numerical modellers were asked to undertake their work and submit their results before the results from the field and laboratory tests are released. Modellers were then invited to submit further (revised) modelling results after receiving the field or lab test results (Aware testing). Results presented in this paper are blind except for laboratory Series #1 where only aware testing was undertaken due to data processing errors.

<table>
<thead>
<tr>
<th>No</th>
<th>Organisation</th>
<th>Country</th>
<th>Modeller</th>
<th>Model(s)</th>
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<tr>
<td>1.</td>
<td>HR Wallingford</td>
<td>UK</td>
<td>Mohamed Hassan</td>
<td>HR Breach</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NWS BREACH</td>
</tr>
<tr>
<td>2.</td>
<td>Cemagref</td>
<td>France</td>
<td>Andre Paquier</td>
<td>Simple model</td>
</tr>
<tr>
<td>3.</td>
<td>UniBW</td>
<td>Germany</td>
<td>Karl Broich</td>
<td>Deich P</td>
</tr>
<tr>
<td>4.</td>
<td>ARS-USDA</td>
<td>USA</td>
<td>Greg Hanson</td>
<td>SIMBA model</td>
</tr>
<tr>
<td>5.</td>
<td>Delft Hydraulics</td>
<td>Holland</td>
<td>Henk Verheij</td>
<td>SOBEK Rural Overland Flow</td>
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<tr>
<td>6.</td>
<td>Ecole Polytechnique de Montreal</td>
<td>Canada</td>
<td>Rene Kahawita</td>
<td>Firebird model</td>
</tr>
</tbody>
</table>

Table 2: Researchers who participated in the numerical modelling programme

The following list shows the numerical modelling runs undertaken by the modellers:

Field tests:

Blind runs: Field test 1, 2, 3, 4 and 5.
Aware runs: Field tests 3, 4 and 5.
Lab Tests:

Series #1: Aware runs Lab test 2,4,5,6,7 and 9.
Series #2: Blind runs Lab test 10,11,12,13,14,15,16 and 17

Given the large amounts of data collected through the field and laboratory modelling work, it was not practical for all modellers to undertake blind and aware simulations for all data sets. Priorities were placed as follows:

1. Model field test cases
2. Model lab test cases matching field test cases
3. Model other lab test cases

3.2 Results collected

Extensive data sets have been collected from the numerical modelling exercise. All results have been plotted and an initial review of performance made. A breach modelling workshop was held at HR Wallingford on 21-23 April 2004, where field, lab and numerical modelling data was reviewed. Conclusions from this workshop may be found in the workshop notes. Overall conclusions from model comparisons are given in Section 4 below.

4 NEW APPROACHES TO BREACH FORMATION MODELLING

4.1 Objectives and approach

IMPACT project objectives relating to breach of dams and embankments comprise:

- Advancement of breach modelling (breach formation) capabilities through field, lab and numerical modelling work
- An assessment of breach modelling uncertainty (WP5)
- Investigation of factors leading to breach location (in linear flood defences) (WP2/WP6)

4.2 Analysis and findings

4.2.1 Breach Formation Modelling

Whilst it will always be possible to improve predictive models for breach formation, it is also helpful to try and assess the performance of existing models and to give some guidance as to which models may be most appropriate for use (in various conditions).

Based upon a methodology proposed by Mohamed (2002), an indicative ranking was obtained for the models that participated in the IMPACT numerical modelling programme. Initial rankings were obtained by combining measures of the accuracy of the predictions of the peak outflow, water level at peak outflow, time to peak, and final breach width (see Tables 3a-3d). Note that not all models performed all tests and hence a range of tables is presented showing comparisons of various modelling results (e.g. compare model performance for the same set of tests rather than overall averaged figures). A range of weightings for combining different performance measures (such as peak discharge, breach width etc) are also given. These are relevant if you are looking for model performance related to a specific output such as peak discharge.

When reviewing Tables 3a-3d it should also be noted that:

- some models simulate composite structures – others not
• some models (such as Simba) have been developed purely for simulating cohesive embankments
• some models are complex predictive models, whilst others are far simpler

(Details of the nature of each model may be found in the WP2 technical report)

From these tables HR BREACH appears to perform consistently well and NWS BREACH consistently poorly. However, when choosing a model for a given application it is recommended that the following points are considered:
• Do you need to simulate a composite or homogeneous structure?
• Do you need to simulate erosion of cohesive or non-cohesive material? Is head cutting likely to occur?
• Do you need a quick and approximate estimate of peak discharge, or as reliable and detailed estimate of a flood hydrograph as possible?
• Do you need to undertake uncertainty analysis of your simulation? Is Monte Carlo sampling required?
• What is the nature of your embankment? How does this match any data upon which a given breach model or equation may be calibrated?

4.2.2 Breach Modelling Uncertainty
An approach combining sensitivity analysis and Monte Carlo sampling has been developed which provides a practical approach to assessing the magnitude of uncertainty within breach modelling. Details of this approach are given under WP5. When applied to the Tous case Study, results suggested that the band of uncertainty around prediction of peak discharge for in the order of ±50%. Best estimates of peak discharge are therefore be within this range of accuracy.

4.2.3 Breach Location
The aim of work here was to investigate potential approaches / methodologies for identifying the relative risk of breach occurring along long lengths of flood defence embankment. This problem may be viewed from a number of perspectives, namely:
• Investigation of physical processes and factors contributing to breach formation through an embankment (and hence identification of key indicators or parameters for inclusion within a model framework or asset inspection / management system)
• Development of a framework for assessment based upon ‘available knowledge’
• Assessment of flood risk, regardless of specific breach location (i.e. ‘what if’ approach to modelling inundation from breach

Physical Factors Affecting Breach Location
Research under WP6 includes the collation and analysis of data relating to breach of embankments across Hungary and the Czech Republic. The focus of this work is the collation of embankment condition, material and failure process data to allow identification of key parameters and processes. Conclusions from this work have not yet been reported.

Framework for Assessment Based Upon Available Knowledge
Work in this area has advanced significantly in the UK through the Defra / EA flood defence research programme. An integrated approach based upon representation of flood defence structures, such as embankments, through the use of fragility curves (load – performance curves) is being developed and will provide a mechanism for identifying the relative risk of
### Table 3a: Overall model performance scores (regardless of number of runs)

<table>
<thead>
<tr>
<th>Weighting Factors</th>
<th>Average Score - All models that performed all tests</th>
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<tr>
<td>PO:1 TP:1 WLP:0 PWL:0</td>
<td>HR BREACH 8.1, HR BREACH 8.7, HR BREACH 8.9</td>
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<tr>
<td>PO:1 TP:1 WLP:0 PWL:0</td>
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<tr>
<td>PO:1 TP:1 WLP:0 PWL:0</td>
<td>HR BREACH 9.9, HR BREACH 10.0, HR BREACH 10.1</td>
</tr>
</tbody>
</table>

### Table 3b: Overall model performance scores (only models performing all tests)

<table>
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<tr>
<th>Weighting Factors</th>
<th>Average Score - All models that performed all runs</th>
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<tbody>
<tr>
<td>PO:1 TP:1 WLP:0 PWL:0</td>
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<tr>
<td>PO:1 TP:1 WLP:0 PWL:0</td>
<td>HR BREACH 9.9, HR BREACH 10.0, HR BREACH 10.1</td>
</tr>
</tbody>
</table>

**Note:** The tables show the average scores for various models across different weighting factors. Each model is evaluated based on its performance in terms of peak outflow, time to peak, final breach width, and other factors.
### Table 3c: Overall model performance scores (comparing tests completed by Sobek model)

<table>
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<th>PO</th>
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### Table 3d: Overall model performance scores (comparing tests completed by Simba model)

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<td>0</td>
<td>1</td>
<td>6.7</td>
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</table>

Note: The average scores are calculated based on the performance of each model in predicting various hydrological parameters such as peak outflow, time to peak, final breach width, and peak flow level.
breach formation along linear flood defence embankments. Details of this work can be found in the WP2 technical report.

Assessment of Flood Risk Resulting from Multiple Breach Locations
An investigation of this approach to modelling has been undertaken by Karl Broich (UniBwM). Overview papers are given in the 4th IMPACT workshop notes.

4.3 Key conclusions and recommendations
Conclusions from WP2 research on breach formation may be divided into a number of sections, as follows:

4.3.1 Understanding the breach formation process
Key processes that were evident from field and laboratory tests include:
- breach side walls are typically vertical during breach development (not trapezoidal as many breach models suggest)
- whilst continuous erosion is likely to occur, lateral erosion is normally through failure of discreet sections of embankment. The size of these discreet sections can vary from small to significant. Removal of this failed material is often very quick and not through steady erosion (i.e. carried out of the breach area by force of flow)
- cohesive material tends to show initial embankment erosion through head cutting (creation of steps) rather than uniform erosion of the face. This may affect the rate at which erosion of the crest/upstream face initiates and hence would be particularly relevant when trying to improve model accuracy in relation to breach initiation and timing
- the rate of breach formation is particularly dependent upon soil properties and embankment condition [e.g. cohesive/non cohesive; compaction; water content].
- Breach location (across an embankment dam for example) significantly affects the formation rate. Where lateral growth is restricted in one direction, erosion rates in the other direction do not compensate.
- Embankment structure is significant. A composite structure (e.g. core and outer layers) will erode differently to a homogeneous embankment. The degree to which the core material dictates the rate of lateral erosion is unclear, but a significant role is thought likely. Interaction between a core structure and supporting fill material dictates the rate of breach growth (in comparison to uniform erosion of a homogeneous embankment).

4.3.2 Breach formation modelling
- Our ability to predict breach formation and the accuracy of breach models has improved as a result of the IMPACT project. Understanding of the breaching process has improved; model performance enhanced. However, whilst advances have been made, these can be significantly improved by further detailed analysis of the data collected.
- The breach formation process is complex, and depends upon a range of parameters including hydraulic loading, and the design and condition of the embankment. Existing numerical models tend to simplify the processes and can help to reinforce misunderstandings as to the real process (e.g. breach shape is typically with vertical walls, not trapezoidal as often quoted by models. Trapezoidal shapes develop after the breach formation process when embankment material dries and slumps.)
- An assessment of breach model performance has been made, with results scored and ordered. However, it is clear that all models have difficulty in accurately predicting breach
dimensions. Consequently, it can be assumed that all models also contain other factors which incorrectly compensate for this ‘physical’ error.

- The uncertainty analysis for the Tous Case Study suggests an uncertainty band for predicting the peak discharge of $\pm 50\%$. Best estimates of peak discharge are therefore within this range of accuracy.

- Model performance varies significantly with the choice of sediment transport equation. Choice of equation is historically often related to common practice within a particular country that a review of the basis of the equation. Care is needed when selecting an equation to ensure that it is relevant for the application.

- Model performance varies significantly when composite structures are simulated by averaging soil parameters and assuming a homogeneous embankment. This can result in differences of several hundred percent in predicting peak discharge (for example).

- Of the models tested, those attempting to predict breach growth through the calculation of discreet failure rather than steady state erosion appeared to perform better (i.e. HR BREACH and DEICH models). This suggests that the approach of integrating aspects of soil mechanics, structure failure and hydraulics is a reasonable approach. The NWS BREACH model, which predefines the erosion pattern appears to perform worst.

### 4.3.3 Recommendations

- Performance tables for the breach models involved in this project have been given and the data has been presented in a number of ways to try and aid understanding. When choosing a model for a particular application care should be taken to ensure that the user understands the basis upon which the model operates and hence where it may or may not be applied (reasonably). Factors to consider include:
  - applicability of sediment equations
  - quick peak discharge approach or slower predictive model approach
  - ability to simulate composite and homogeneous embankments
  - ability to predict breach growth freely rather than through a predefined shape
  - use of soil and embankment condition parameters
  - need for Monte Carlo analysis

Caution is recommended where the use of ‘standard’ 2D flow models combined with sediment transport equations is proposed. Whilst this approach has not been directly compared within these studies, the findings that for a more reliable result, it is necessary to include assessment of soil mechanics and structural processes, are inconsistent with the (current) application of these models.

- The programme of work under the IMPACT project placed a great emphasis on data collection in order to collect reliable breach data sets. This has been achieved. However, processing and analysis of this data has been considerably more difficult than envisaged. Consequently, whilst initial review and analysis has been undertaken, resulting in progress in terms of model performance and breach understanding, greater advances could now be achieved by a more in depth analysis of this valuable data. Such analysis work needs to be integrated into planned international research programmes during the coming 1-2 years.
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6 REFERENCES
To be added